Dijet Production at Hadron Colliders in Theories with Large Extra Dimensions

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Abstract:

We consider the production of high invariant mass jet pairs at hadron colliders as a test for TeV scale gravitational effects. We find that this signal can probe effective Planck masses of about 10 TeV at the LHC with center of mass energy of 14 TeV and 1.5 TeV at the Tevatron with center of mass energy of 2 TeV. These results are compared to analogous scattering processes at leptonic colliders.

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Gravitation is by far the weakest force of nature. Indeed, the usual explanation of this is that quantum gravitational effect only become important at the Planck mass scale $M_P = G_N^{-1/2} = 1.22 \times 10^{19}\ GeV$. The fact that this scale is so much higher than the Standard Model (SM) electroweak scale of $O(100\ GeV)$ leads to the hierarchy problem that fine tuning of the parameters of the SM at the Planck scale are required to keep the electroweak scale small. In general this may be solved by supposing that new physical processes, such as SUSY or new strong interactions, become manifest at the TeV scale. Such new phenomena can thus lead to a low energy effective theory that does not depend on the exact parameters of physics at the Planck scale.

Many string theories such as M-theory [1] can only be consistent if there are more than 3+1 dimensions, presumably the extra dimensions would form a compact manifold. This leads to the recent suggestion of [2, 3] that gravity, which is weak at macroscopic scales, but may become strong at TeV scales. In particular, if there are n compact dimensions of length R, at distances $d < R$ the Newtonian inverse square law will fail [2] and the gravitational force will grow at a rate of $1/d^{n+2}$. If R is sufficiently large, even the weak strength of gravitational force at the macroscopic scale can lead to a strong force at distances of $1\ TeV^{-1}$. For this to happen, the size of the extra dimension should be:

$$8\pi R^n M_S^{2+n} \sim M_P^2 \ . \tag{1}$$

where M_S is the effective Planck scale of the theory which is the mass scale at which quantum gravitational effects become important. There is no hierarchy problem if the scale M_S is $O(1\ TeV)$ i.e. not far beyond the electroweak scale. For instance, if $n = 1$ and M_S=1 TeV, then R is of the order of $10^8\ km$, large on the scale of the solar system and clearly ruled out by astronomical observations. However, if $n \geq 2$ and $M_S \geq 1\ TeV$ then $R < 1\ mm$; there are no experimental constraints on the behavior of gravitation at such distance scales [4]. This compactification is thus not ruled out based on gravitational experiments (there are however alternative schemes which can consistently allow one extra dimension such as in [5]).

Of course all other forces and particles appear to exist in the usual 3+1 dimensions. In the proposed scenario of [2] this results from the existence of a 3+1 dimensional brane to which all known fermions and gauge fields are confined in the total of 3+n+1 dimensional space. Only gravitation can propagate through the bulk and therefore may directly be sensitive to the effects of the new dimensions.

Thus, gravitational effects can become important at TeV scale colliders. In particular, the onset of strong gravitational effects may be understood by perturbative couplings of

matter to gravitons leading to observable effects due to the production of real graviton states or the exchange of virtual gravitons at energies approaching M_S.

To calculate such perturbative gravitational effects, it is useful to adopt the 4-dimensional point of view. We therefore interpret the graviton states which move parallel to the 4 dimensions of space time as the usual massless graviton giving rise to Newtonian gravity, while the graviton states with momentum components perpendicular to the brane are effectively a continuum of massive objects. The density of graviton states is given by [2, 3, 6, 7]:

$$\rho(m^2) = \frac{dN}{dm^2} = \frac{m^{n-2}}{G_N M_S^{n+2}} \tag{2}$$

where m is the mass of the graviton.

Furthermore, gravitons with polarizations that lie entirely within the physical dimensions are effective spin 2 objects. Gravitons with polarizations partially or completely perpendicular to the physical brane are vector and scalar objects. In this letter, we will primarily be concerned with the effects of the exchange of virtual spin 2 gravitons. To perform perturbative calculations in this theory, one can formulate Feynman rules for the coupling of graviton states to ordinary particles where $\kappa = \sqrt{16\pi G_N}$ is the effective expansion parameter [6, 7], in particular, we adopt the conventions of [7].

In the case of the exchange of virtual graviton states, one must add coherently the effect of each graviton. For instance, in the case of an s-channel exchange, the propagator is proportional to $i/(s - m_{G_\lambda}^2)$ where m_{G_λ} is the mass of the graviton state G_λ. Thus, when the effects of all the gravitons are taken together, the amplitude is proportional to

$$\sum_\lambda \frac{i}{s - m_{G_\lambda}^2} = D(s). \tag{3}$$

If $n \geq 2$ this sum is formally divergent as m_{G_λ} becomes large. We assume that the distribution has a cutoff at $m_{G_\lambda} \sim M_S$, where the underlying theory becomes manifest. Taking this point of view, the value of $D(s)$ is calculated in [6, 7]:

$$\kappa^2 D(s) = -i\frac{16\pi}{M_S^4} F + O(\frac{s}{M_S^2}) \ . \tag{4}$$

The quantity F contains all the dependence on n and is given by:

3

$$F = \begin{cases} \log(s/M_S^2) & \text{for } n = 2 \\ 2/(n-2) & \text{for } n > 2 \end{cases} \quad . \tag{5}$$

In a $2 \to 2$ process, a similar expression will apply for t and u channel exchanges. If $n > 2$, $D(s)$ is independent of s in this approximation and likewise the sum of the propagators in the t and u channels will be identical. As pointed out in [8], this will not necessarily be a good approximation in the case of $n = 2$ because of the logarithmic dependence of D on s.

The theory formulated in this way does not treat the cutoff in detail but makes the ad hoc assumption that the cutoff is M_S. However, bounds which are obtained in this way may be applied to a more specific theory by computing an effective M_S which would follow from the parameters of a given theory. We can thus investigate the phenomenology which may occur at various colliders [8]-[9] as well as precision experiments [10]. The assumption that the cutoff is $O(M_S)$ may be realized in a natural way from recoil effects of the brane as discussed in [11], which gives rise to an exponential cutoff in the coupling to gravitons with a mass greater than the stiffness of the brane. In general the theory may be cut off by whatever new physical processes become manifest at M_S.

In attempting to place limits on such theories at a hadronic collider, the most natural process to consider is one which produces real gravitons. For instance, if such gravitons were produced in association with a jet, the monojet + large missing P_T signal should be unmistakable. Indeed this process was considered in [12] and it was found that a bound of $M_S = 1.3$, 0.9, 0.8 TeV may eventually be achieved at the Tevatron for $n = 2$, 4 and 6, respectively. At the LHC these bounds may may be extended to $M_S = 4.5$, 3.4 and 3.3 TeV for $n = 2$, 4 and 6. The analogous process at the NLC, $e^+e^- \to \gamma G$ (G =graviton), was also considered in [12, 13] giving a reach at $\sqrt{s} = 1\,TeV$ of $M_S = 7.7$, 4.5 and 3.1 TeV for $n = 2$, 4 and 6. Slightly better bounds may be obtained in the case of an $e\gamma$ collider based on a 1 TeV e^+e^- collider where the reaction would be $e\gamma \to eG$ [14].

For such processes which produce real gravitons, the cross section is proportional to $(E/M_S)^{n+2}$ so that at larger n less stringent bounds can be placed on M_S. At $n = 2$, there are also astrophysical constraints, both from the rate of supernova cooling [15, 16] which requires that $M_S > 30\,TeV$, and the absence of a diffuse cosmic gamma ray background from the decay of relic gravitons [15, 17], which requires $M_S > 130\,TeV$. This latter bound, however, depends strongly on the assumption that all the decay modes of the graviton are governed by the perturbative decay modes.

While real graviton production bounds M_S most stringently in the case where $n = 2$, virtual processes tend to give better bounds in the case where $n > 2$. In particular, we

4

consider the observation of gravitational effects in 2 jet events at hadron colliders, either $pp \rightarrow 2\ jets + X$ or $p\bar{p} \rightarrow 2\ jets + X$. As can be seen from eq. (5) the bounds obtained in virtual graviton exchange events will be relatively independent of n.

It should also be kept in mind that the TeV scale gravitational theories imply the existence of new physics at the scale of M_S which may also lead to two jet processes, such as discussed in [18]. Thus, in experimentally probing the two jet signal, or indeed any manifestation of virtual graviton exchange, one can only place limits on the gravitational effects common to all such models. If a signal is seen, of course, further investigation and observations in other channels is required to determine if the effects are purely gravitational or if other physics is the cause. Here we shall confine ourselves to a discussion of the limit that can be placed on the effective M_S from two jet events generated by graviton exchanges.

At the parton level, two jet events are generated via processes of the form $\rho_1\rho_2 \rightarrow \rho_3\rho_4$. where ρ_ℓ are partons (of momentum p_ℓ). In particular, the possible parton level processes are as follows:

$$
\begin{aligned}
&(a)\ q\bar{q} \rightarrow q'\bar{q}' \quad (b)\ qq' \rightarrow qq' \ / \ q\bar{q}' \rightarrow q\bar{q}' \quad (c)\ qq \rightarrow qq \\
&(d)\ q\bar{q} \rightarrow q\bar{q} \quad\ \ (e)\ gg \rightarrow q\bar{q}/q\bar{q} \rightarrow gg \qquad\ (f)\ gq \rightarrow gq \ / \ g\bar{q} \rightarrow g\bar{q} \\
&(g)\ gg \rightarrow gg,
\end{aligned}
\tag{6}
$$

where q represents some flavor of quark and $q' \neq q$ is a distinct flavor.

Of course each of these scattering processes has a SM contribution which the gravitational amplitudes will interfere with (where allowed by color conservation). We shall see however that since the amplitude grows with s^2, scattering through gravitons tends to be harder and is easily separated from SM processes which drop with s.

The tree-level hard cross-sections σ_i for a given subprocesses i, including the gravitational effects and their interference with the SM, can be written in the form:

$$
\frac{d\sigma_i}{dz} = k_s \left[\frac{\pi\alpha_s^2}{2s} f(z) - \frac{2\pi\alpha_s F}{s} \frac{s^2}{M_S^4} g(z) + \frac{8\pi F^2}{s} \frac{s^4}{M_S^8} h(z) \right]
\tag{7}
$$

where $z = p_1 \cdot (p_4 - p_3)/p_1 \cdot p_2$ is the center of mass scattering angle and $s = (p_1 + p_2)^2$. In the limit where the mass of the quarks is neglected, the formulas for $f(z)$, $g(z)$ and $h(z)$ and k_s are given in Table 1 where the SM part agrees with the calculations given for example in [19]. Note that in cases where there are two identical particles in the final state, a factor of $1/2$ is included in k_s so in all cases phase space should be integrated over the range $-1 \leq z \leq +1$.

5

Table 1

Process	k_s	f(z)
$q\bar{q} \to q'\bar{q}'$	$1/36$	$8(1+z^2)$
$qq' \to qq'; \; q\bar{q}' \to q\bar{q}'$	$1/36$	$16\frac{5+2z+z^2}{(1-z)^2}$
$qq \to qq$	$1/72$	$\frac{32}{3}\frac{(z^2+11)(3z^2+1)}{(1-z^2)^2}$
$q\bar{q} \to q\bar{q}$	$1/36$	$\frac{8}{3}\frac{(7-4z+z^2)(5+4z+3z^2)}{(1-z)^2}$
$gg \to q\bar{q}$	$1/256$	$\frac{16}{3}\frac{(9z^2+7)(1+z^2)}{1-z^2}$
$gq \to gq$	$1/96$	$\frac{32}{3}\frac{(5+2z+z^2)(11+5z+2z^2)}{(1+z)(1-z)^2}$
$gg \to gg$	$1/512$	$288\frac{(3+z^2)^3}{(1-z^2)^2}$

Process	g(z)	h(z)
$q\bar{q} \to q'\bar{q}'$	0	$\frac{9}{256}(1-3z^2+4z^4)$
$qq' \to qq'; \; q\bar{q}' \to q\bar{q}'$	0	$\frac{9}{2048}(149+232z+114z^2+16z^3+z^4)$
$qq \to qq$	$-4\frac{5-3z^2}{1-z^2}$	$\frac{3}{1024}(547+306z^2+3z^4)$
$q\bar{q} \to q\bar{q}$	$-\frac{1}{4}\frac{(11-14z-z^2)(1+z)^2}{1-z}$	$\frac{3}{2048}(443+692z+354z^2+116z^3+107z^4)$
$gg \to q\bar{q}$	$-4(1+z^2)$	$\frac{3}{8}(1-z^4)$
$gq \to gq$	$2(5+2z+z^2)$	$\frac{3}{8}(1+z)(5+2z+z^2)$
$gg \to gg$	$120(3+z^2)$	$\frac{9}{4}(3+z^2)^2$

Table 1: In this table, we give the value of k_s and the functions $f(z)$, $g(z)$ and $h(z)$ which define the differential cross section in eq. (7) for each of the $2 \to 2$ processes relevant to dijet production in hadron collisions. The variable z is the scattering angle in the center of mass frame given by $(t-u)/s$ and in all cases the total cross section is given by integrating z over the range $-1 \le z \le +1$.

The total differential two jet cross sections is shown in Fig. 1 at the LHC pp collider with $\sqrt{s_0} = 14\ TeV$, for $M_S = 2$, 4, 6 and the SM alone and at the Tevatron $p\bar{p}$ collider with $\sqrt{s_0} = 2\ TeV$, for $M_S = 0.75$, 1.5 and the SM alone. Here, s_0 is the square of the center of mass energy of the hadronic collision and $\tau = s/s_0$. In all cases we have imposed the cut $|z| < 0.5$ which tends to favor the graviton scattering processes. The fraction of this differential cross section due to various partonic subprocess for the LHC with $M_S = 2\ TeV$ and at the Tevatron with $M_S = 0.5\ TeV$ is shown in Fig. 2(a) and 2(b). Of course, the extrapolation of these curves beyond M_S is not valid since at that point new physical processes, such as the brane recoil effects in [11], will enter and suppress the effect. In Fig. 1 this point is indicated by the black circles and so the portion of the curve to the right of the circles may depend on the cutoff mechanism. In these results we have used the CTEQ4M structure functions, set #1 [20].

In the case of the LHC, one can see that the dominant contributions are from $gg \to gg$ and $qg \to qg$ for $\tau < 0.1$, which results from the dominance of gluons for lower τ. At $\tau > 0.1$, $qq \to qq$ becomes important due to the hard component of the structure functions of the constituent quarks. At the Tevatron, $gg \to gg$ and $qg \to qg$ are dominant at low τ while here $q\bar{q} \to q\bar{q}$ will be dominant at larger τ.

In order to get an idea of what the reach of these signals are, we consider imposing cuts of the form $\tau > \tau_0$ since, clearly, the SM backgrounds are more important at lower τ. In Fig. 3 we show the maximum value of M_S for which the difference between the Standard Model and the Standard Model with gravitation has a 3σ significance both at the LHC and the Tevatron. In this graph we have taken an integrated luminosity for the LHC of 30 fb^{-1} and for the Tevatron of 2 fb^{-1}. From this graph it is apparent that, for an optimal τ_0 cut of ~ 0.2, the reach according to this criterion is $\sim 10\ TeV$, while, for the Tevatron at $\tau_0 \sim 0.2$, the reach is $\sim 1.5\ TeV$. A study [21] of existing CDF and $D0$ two jet data gives a bound of $M_S < 1.2\ TeV$.

A related process which has been previously considered [22] is the Drell-Yan process which at hadron colliders, pp or $p\bar{p} \to e^+ e^- + X$. In that case, at a $\sqrt{s_0} = 14\ TeV$ LHC, with integrated luminosity of 30 fb^{-1}, one obtains a reach of about 5.6 TeV, while at the Tevatron with $\sqrt{s_0} = 2\ TeV$, given an integrated luminosity of 2 fb^{-1} one obtains a reach of 1.3 TeV.

It is interesting to compare these two jet results to those which may be obtained at the NLC by studying $2 \to 2$ scattering processes. Many such processes have been considered in the literature [22, 23, 24]. In particular it was pointed out in [24] that the $e^- e^- \to e^- e^-$ mode does somewhat better than the $e^+ e^-$ modes at the same luminosity. For the sake of definiteness, let us consider the reach of a $e^+ e^-$ or $e^- e^-$ collider with $\sqrt{s} = 1\ TeV$ and integrated luminosity of 100 fb^{-1}, where we impose a cut on the two final state particles

of $|z| < 0.5$. In this case we find that the reach in M_S is $7\ TeV$ for $e^+e^- \to \mu^+\mu^-$, $4\ TeV$ for $e^+e^- \to 2\ jets$, $5.5\ TeV$ for $e^+e^- \to \gamma\gamma$, $8.5\ TeV$ for $e^+e^- \to e^+e^-$ and $9.2\ TeV$ for $e^-e^- \to e^-e^-$.

Another proposed mode of operation of an NLC is to convert it into a gamma gamma collider by scattering optical frequency laser beams off of the electron beams [25]. This allows, for instance the study of $\gamma\gamma \to \gamma\gamma$, where there is no tree level SM background. The leading SM contributions is given by the box diagram derived in [26]. These processes were studied extensively in [8, 27] where in [8] detailed consideration is given to optimization of the cuts and polarization of the photons and the electrons. A reach of $3.5\ TeV$ is thus obtained for $n = 6$ and likewise $3.8\ TeV$ for $n = 4$ based on an NLC with electron-positron center of mass energy $\sqrt{s_{ee}} = 1\ TeV$. Of course one may also consider a NLC where only one of the electron beams is converted into a photon beam. At such a collider, one may study $e^\pm\gamma \to e^\pm\gamma$. For this process a reach of $M_S \sim 7.5\ TeV$ is found [28], again for $n = 4$ based on an NLC with electron-positron center of mass energy $\sqrt{s_{ee}} = 1\ TeV$ and an integrated luminosity of $100\ fb^{-1}$.

The case of two photons going to two jets, $\gamma\gamma \to q\bar{q}$ and $\gamma\gamma \to gg$, has been considered in detail in [29]. They find that in a $\gamma\gamma$ collider based on a $500\ GeV$ electron-positron machine, the sensitivity is $(3.2, 2.8)\ TeV$ for $n = (4, 6)$ while the sensitivity is $(11.1, 9.4)\ TeV$ at a $2\ TeV$ machine.

In conclusion then, two jet signals at the LHC can give a reach of about $10\ TeV$ for M_S which is quite favorable to the reaches obtainable via Drell-Yan ($5.8\ TeV$) and monojet signals (i.e. $4.5; 3.3\ TeV$ for $n = 2; 6$). An NLC collider running in e^-e^- mode could achieve comparable reaches i.e., $8.5\ TeV$, however it is unclear if such a collider would run extensively in this mode. In e^+e^- mode, of the processes considered, e^+e^- gives the best reach of $6.8\ TeV$. Even though there are large SM backgrounds to the dijet cross section at hadronic colliders, the fact that graviton exchange dominantly contributes only at the highest values of τ makes this signal viable.

Figure Captions

Figure 1 The total differential cross sections $d\sigma/d\tau$ are shown as a function of τ for $n = 4$ where the acceptance cut $|z| \leq 0.5$ has been imposed for various values of M_S. Solid lines represent the contribution at the LHC ($\sqrt{s_0} = 14\ TeV$) if $M_S = 2\ TeV$ (upper solid line), $4\ TeV$, $6\ TeV$ and the Standard Model alone (lower solid line). The dashed lines represent the contributions at the Tevatron ($\sqrt{s_0} = 2\ TeV$) if $M_S = 0.75\ TeV$ (upper dashed line), $1.5\ TeV$ and the Standard Model alone (lower dashed line). The circles indicate where $M_S^2 = \tau s_0$.

Figure 2 $(d\sigma_i/d\tau)/(d\sigma/d\tau)$ as a function of τ for each partonic mode with $n = 4$ is shown; in Fig. 2(a) the LHC is considered with pp collisions at $\sqrt{s_0} = 14\ TeV$ taking $M_S = 2\ TeV$ while in Fig. 2(b) the results for the Tevatron is considered with $p\bar{p}$ collisions at $\sqrt{s_0} = 2\ TeV$ taking $M_S = 0.5\ TeV$. In both cases a cut of $z < 0.5$ is imposed. The subprocesses are $q\bar{q} \rightarrow q'\bar{q}'$ (thin dashed line); $qq' \rightarrow qq'$ (thin dotted line); $q\bar{q}' \rightarrow q\bar{q}'$ (thick dot dash line); $qq \rightarrow qq$ (thin dot dash line); $q\bar{q} \rightarrow q\bar{q}$ (thick dotted line); $gg \rightarrow q\bar{q}$ (thick long dashed line); $q\bar{q} \rightarrow gg$ (thin solid line); $qg \rightarrow qg + \bar{q}g \rightarrow \bar{q}g$ (thick dashed line); $gg \rightarrow gg$ (thick solid line).

Figure 3 The reach of the Tevatron and LHC in the case of $n = 4$ as a function of a lower cut in τ based on the total cross section as in Fig. 1. In both cases a criterion of 3 sigma was used. In the LHC case an integrated luminosity of 30 fb^{-1} was assumed while in the case of the Tevatron an integrated luminosity of 2 fb^{-1} was assumed.
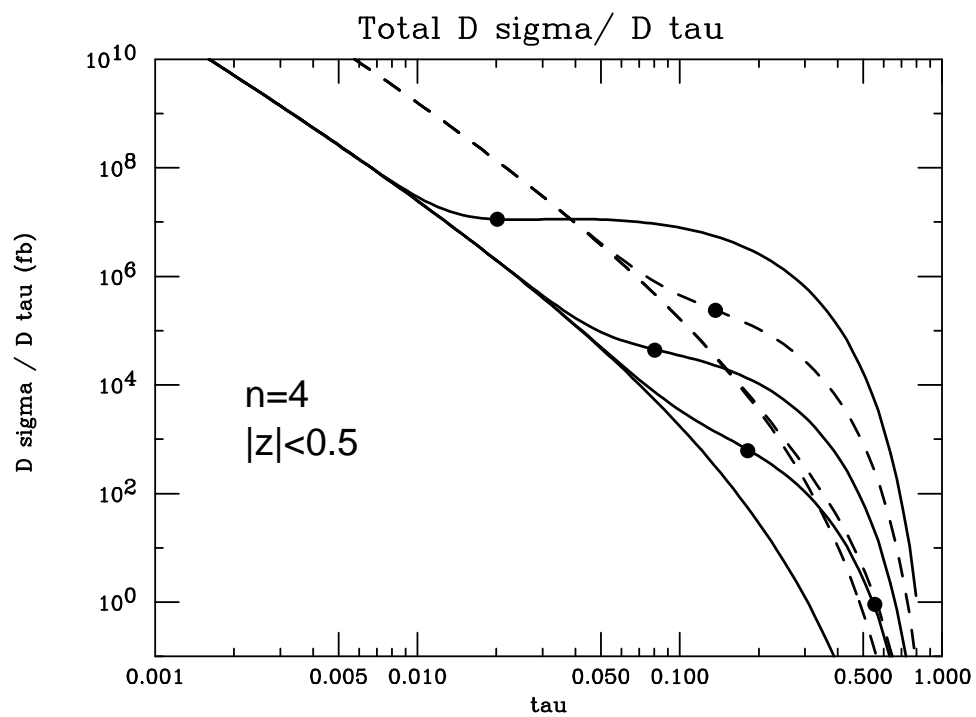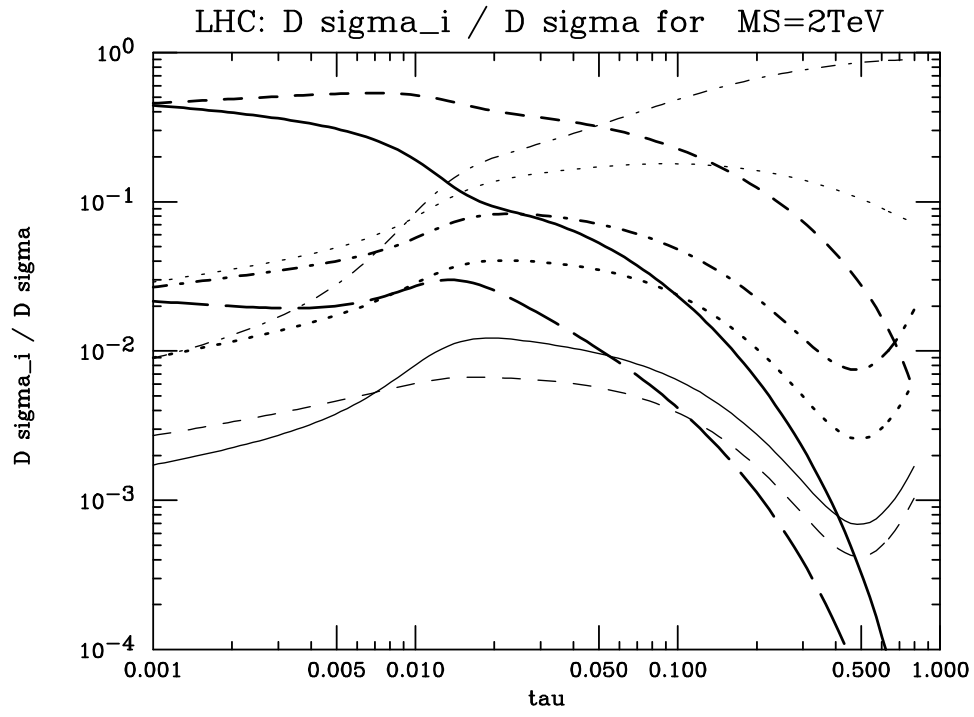
Figure 1

Total D sigma/ D tau

n=4
|z|<0.5

D sigma / D tau (fb)

tau

Figure 2(a)

LHC: D sigma_i / D sigma for   MS=2TeV

Figure 2(b)

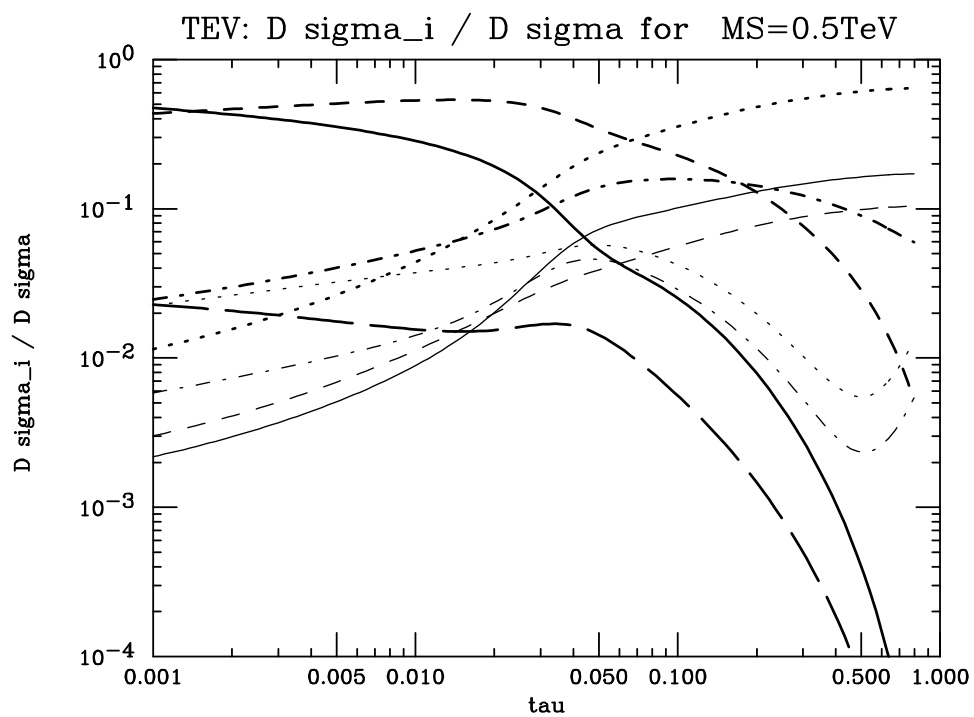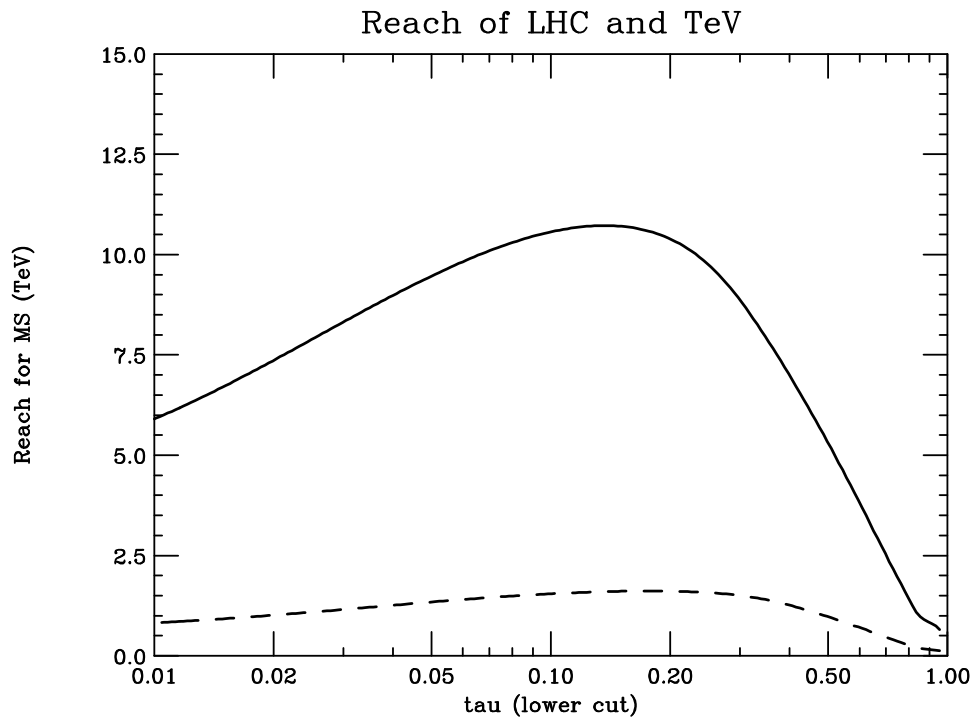TEV: D sigma_i / D sigma for   MS=0.5TeV

Figure 3

Reach of LHC and TeV

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